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13. ABSTRACT (Maximum 200 words)

This project focused on fast numerical modeling of ultra-wideband (UWB) electromagnetic induction (EMI) sensing of buried unexploded ordnances (UXO'S). Modeling of the "targets" (or representative clutter objects), the soil environment, and the two in combination were treated. Two example sensors were modeled specifically, one working in the frequency domain (FD), the other in the time domain (TD). The models of UXO response were extremely high fidelity, using the standardized excitations approach (SEA). This includes all effects, and all internal interactions. At the same time, the models are fast enough to use in essentially real time modeling of contemplated scenarios in which prospective signal patterns are sought over plots of ground on the order of typical survey segments. Models of the ground response include ultra-fast code that evaluate analytical solutions for responses of magnetically permeable and conductive environments to the subject instruments, with algorithms for generalization to other instruments.

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Enclosure 1

Fast Forward Modeling of EMI Responses from Subsurface Metallic Objects and Ambient Environments

Final Technical Progress Report: Agreement W911NF-05-1-0455

August 23, 2006

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Contents

1 Project Statement

This project focused on fast numerical modeling of ultra-wideband (UWB) electromagnetic induction (EMI) sensing of buried unexploded ordnances (UXOs). Modeling of the "targets" (or representative clutter objects), the soil environment, and the two in combination were treated. Two example sensors were modeled specifically, one working in the frequency domain (FD), the other in the time domain (TD). The models of UXO response were extremely high fidelity, using the standardized excitations approach (SEA). This includes all effects of sensor field non-uniformity, material and geometrical heterogeneity of the targets, near and far field effects, and all internal interactions. At the same time, the models are fast enough to use in essentially real time modeling of contemplated scenarios in which prospective signal patterns are sought over plots of ground on the order of typical survey segments. Models of the ground response include ultra-fast code that evaluate analytical solutions for responses of magnetically permeable and conductive environments to the subject instruments, with algorithms for generalization to other instruments.

Specific codes developed and tested are

1. Ultra-fast forward models of UXO EMI responses based on the SEA in both the frequency and time domains

2. Fast codes for responses of conductive, permeable soils, for a halfspace, for arbitrarily layered configurations, and for rough surfaces

1.1 Frequency Domain standardized excitations approach (SEA)

Current idealized forward models for electromagnetic induction (EMI) response can be defeated by the characteristic material and geometrical heterogeneity of realistic unexploded ordnances (UXOs). A new, physically complete modeling system was developed that includes all effects of these heterogeneities and their interactions within the object, in both near and far fields. The model is fast enough for implementation in inversion processing algorithms. A method is demonstrated for extracting the model parameters by straightforward processing of data from a defined measurement protocol. Depending on the EMI sensor used for measurements, the process of inferring model parameters is ill-posed. More complete data can alleviate the problem. For a given set of data, special numerical treatment is introduced to take the best advantage of the data and obtain reliable model parameters. The resulting fast model is implemented in a pattern matching treatment of measurements by which signals from a UXO are identified within a series of those from unknown targets. Preliminary results show that this fast model is promising for use in processing of this kind. The inherent difficulties of target identification were examined and solutions for resolving these difficulties are discussed in [1].

1.2 Time Domain standardized excitations approach (SEA)

Electromagnetic induction (EMI) is a prominent technique in unexploded ordance (UXO) detection and discrimination research. Existing idealized forward models for the EMI response can be defeated by both the material and geometrical heterogeneity of realistic UXO. We have developed a new, physically complete modeling system referred to as the Standardized Excitations Approach (SEA), that includes all the effects from these heterogeneities including their interactions within the object and is applicable in both the near and far fields. The excitation field is decomposed into fundamental modes, the response of the given target to any given fundamental mode (denoted as fundamental solutions) is obtained beforehand and saved in a library, so that the target response to an arbitrary excitation field can be calculated via a simple superposition of these fundamental solutions.

The model parameters (i.e. the fundamental solutions) of a given object can be extracted from a sufficiently detailed set of measurement data. Note that these parameters will be specific to each EMI instrument.

The parameter extraction process was developed in [1] for the frequency domain using the GEM-3 EMI instrument. We also applied this SEA to the time domain using the EM-63 instrument as an example. The receiver coil of the EM63 is a 0.5m by 0.5m square loop and can not be approximated by a point receiver. Therefore, in the model, the data is interpreted as the integration of the secondary field over the receiver loop. The objects we consider are all Body of Revolution (BOR) targets. We exploit the fact that the calculated SEA model parameters also exhibit specific behavior because the target is a BOR. The representative magnetic charges that produce the secondary field induced by each fundamental excitation mode should sum to zero. The algorithm is improved by enforcing symmetric properties and zero total magnetic charge, which makes the algorithm more robust and more efficient. Preliminary results show that this approach works well for this time domain EMI instrument. We plan to model the Man Portable Vector (MPV) instrument (currently being fabricated), including 15 receiver coils, using this approach. After optimization, this model may be fast enough for implementation in inversion processing algorithms.

1.3 Soil Response Calculations

Magnetic and electromagnetic induction (EMI) sensing have been identified as two of the most promising technologies for the detection and discrimination of subsurface metallic objects, particularly unexploded ordnances (UXOs). In magnetic sensing, the principle of detection is that the sensor measures a distortion of the Earth's magnetic field caused by ferrous objects/ordnances. Similarly, in EMI, the sensors are detecting signals that are produced by induced and permanent magnetic polarizations. While these sensors can detect ferrous objects, they also find many other magnetic anomalies in the close vicinity. Soils, which contain small magnetic particles, called magnetically susceptible soils, can produce EMI responses, and therefore they can mask or modify the object's EMI signature. These soils are a major source of false positives when searching for UXO using magnetic or EMI sensors. Studies show that in adverse environments up to 30% of identified electromagnetic (EM) anomalies are attributed to geology. Therefore, to enhance UXO detection as well as discrimination under geological field conditions the effects of the magnetic soils on the magnetic and EMI signal demands detailed study. The method of auxiliary sources (MAS) was applied to investigate the EMI response from magnetically susceptible rough surfaces. Several important physical phenomena such as the interaction between surface irregularities, modeled as multi hemitoroidal objects, surface roughness and antenna elevation effects were studied and documented. The numerical results were checked against available measurement data.

2 Summary of Results

2.1 FD-SEA

Reliable techniques for subsurface discrimination are urgently needed to reduce the cost of UXO cleanup. As an inverse problem, UXO discrimination requires a fast forward model, i.e. a model calculating EMI responses for prospective targets that may be present. Several fast models have been developed and employed. One of the most successful is the dipole model [2, 3], in which a target's response is approximated with one or a number of infinitesimal magnetic dipoles, each responding independently to the local value of the impinging transmitted ("primary") field. The dipole model is a good approximation only if the observation position is far enough from the target and if interactions between the components of the target do not affect the far field signal significantly. However, in UXO detection and discrimination the sensor is often close to the target, and we have shown elsewhere that interaction effects can be very significant [4, 5]. Analytical solutions for a spheroid in the EMI frequency range (10's of Hz up to 100's of kHz) have been developed recently [6,7]. Using these solutions, we have shown that the EMI responses of some geometrically complex objects can be approximated effectively by that of a representative spheroid [8, 9].

For more complicated, materially heterogeneous objects, the dipole or spheroid models are not always sufficient, and detailed numerical solution by established methods is too slow to be applied in most inversion or classification schemes. The alternative is a standardized excitation approach, here formulated as a spheroidal mode technique [4, 8, 10, 11]. We choose a set of fundamental excitation modes in spheroidal coordinates. Spheroidal coordinates were selected because they most readily conform to the general shape of the elongated objects of interest. A linear combination of these modes can represent an arbitrary excitation field. The EMI response of the target to each fundamental mode is obtained and saved for subsequent use. Because the system we are studying is linear, if some general excitation field constitutes a particular superposition (linear combination) of inputs, the response will be a corresponding superposition of outputs. Hence, we build a library of canonical UXO forms, where the fundamental solutions (i.e. the response of each UXO to the fundamental excitation modes) are stored. The EMI response of any UXO to an arbitrary excitation can then be constructed from the library data. In the approach described here, we store the modal responses of any particular target in terms of the responses to a set of equivalent sources located mathematically in the object's region. In related work [12], this same kind of formulation and solution archival approach was pursued, requiring only storage of an efficiently reduced set of sources for each excitation mode. In that work the essential responding sources are obtained by applying a physically complete numerical simulation of an object's response to each specifiable mode. Here, we solve for the sources based on measured data. In either case, the crucial point is that these sources do not respond as discrete sources in the independent dipole models. The sources here act together, i.e. not as if they respond only to the excitation field in their vicinities. Together they produce the response of the entire object to the entire excitation by the mode with which they are associated.

For the general case, the fundamental solutions can be obtained indirectly from properly designed measurements, designated here as solution definition (SD) data. This data allows one to compute the unknown coefficients in expressions valid for describing the general solution to the equations that govern the relevant physics. Note that this is fundamentally different from the nature of "data based" models. The latter include most prominently various kinds of regression or least square fits of signal patterns to heuristic or empirical expressions of convenience. Our use of the SD data also differs from "training" an inference or classification system, such as neural nets or support vector machines, which do not rely on the underlying physics. Rather, we evaluate general solutions of the governing equations for objects at hand. Whereas in detailed numerical treatments such as Method of Moments one would solve for comparable unknowns by matching fields at boundary locations, here we match data at chosen observation points instead.

A major task in the spheroidal mode approach comes from the fact that the excitation fields from realistic EMI sensors are usually a combination of the fundamental modes, so the coefficients in the fundamental solution have to be obtained through an inversion procedure, which often suffers from ill-conditioning. We have developed several techniques to treat the ill-conditioning problem [13, 14]. For a given set of measurements, we sort the fundamental modes in the primary field and keep only those terms whose coefficients are not negligible. All other terms are truncated. Then, the fundamental solutions are obtained via a weighted least square error algorithm, in which weighting functions are applied so that all eligible observation data make significant contributions to the cost function.

We have demonstrated the application of this spheroidal mode approach to UXO identification. The forward model is applied in a pattern matching algorithm, in which the fundamental solutions for the candidate(s) sought are known. For a set of measurements on an unknown target, optimization determines the candidate's location and orientation such that the calculated scattered field best matches the measurement observations. The goodness of fit at the optimal location and orientation provides a basis for acceptance or rejection of the candidate as the object producing the measured data.

The fundamental excitation approach can be applied in both time and frequency domains. We focussed on frequency domain analysis. As indicated below, one can easily apply the system in the time domain, by replacing frequency points in the formulations with time points.

2.2 TD-SEA

Application of SEA to a time domain EMI sensor involved similar development to Sec. 2.1. Specific contribution and results concerning this time-domain formulation include:

1. modification of the FD approach to the time domain
2. loop receiver instead of point receiver (signal integrated over receiver coil)
3. enforcing zero total magnetic charge
4. enforcing BOR properties

2.3 Soil Response

Unexploded ordnance (UXO) detection and neutralization are emerging environmental issues around the world. In the USA alone there are as many as 11 million acres of land and about one million acres of underwater environments that are potentially contaminated with UXO. UXO items include artillery shells, bullets, mortars, bombs and are relatively large metallic objects. While metal detectors can find UXO, they also other metals in the vicinity. This is particularly a problem in highly contaminated UXO cleanup sites, where multiple subsurface objects appear within the field of view of the electromagnetic induction (EMI) sensor simultaneously. The task of discriminating UXO from non-UXO items is much more complicated when sensor data is contaminated with geological noise originating from magnetic soils.

Magnetic soils are a major source of false positives when searching for landmines or UXO with electromagnetic induction sensors. Recent studies [15–19] showed that, magnetically susceptible soils can produce electromagnetic anomalies of the same magnitude as buried metallic targets. Under adverse conditions up to 30% of identified electromagnetic (EM) anomalies are attributed to geology [15]. Several studies have been conducted to understand the interaction between the object and host magnetic soil [17], and to distinguish between anomalies originating from UXO and geology. In parallel several discrimination techniques that generally include a combination of (a) spatial filtering of the data and (b) comparing the EM response of the soil to a soil model have been developed. Some UXO discrimination studies have showed how important it is to include magnetic soil models into inversion algorithms when the response of the soil closely matches the response of a target [18, 19].

In those studies, it is assumed that the spatial distribution of magnetic anomalies are constant, similar to a half space, and that this response can be subtracted from measured data. This process is only partially effective, yet even in areas of very flat smooth magnetic soil and under controlled conditions, variations in sensor height and orientation, as well as small variations in the surface topography, can produce anomalies similar to those from UXO [20]. Due to the difficulties in spatially distinguishing between soil and metal anomalies, it is important to study in detail the EMI response from magnetically susceptible soils with a rough surface profile.

A main objective of our work has been to study EMI response from magnetically susceptible soils with a rough surface, and to understand how spatially distributed anomalies/roughness affects EMI responses from a UXO detection and discrimination perspective. To do so, the full EM problem has been solved using a numerical approach called the method of auxiliary sources (MAS) [12, 21–23]. For the low frequencies of interest here, induced conduction currents are much stronger than the displacement currents inside the UXO, so the latter can be neglected. Electric fields are typically negligible in the EMI frequency range. Thus, given the low frequency range characteristic of EMI sensing (10's of Hz to perhaps 100 kHz), the dielectric properties of the surrounding media are relatively unimportant for EMI identification of buried targets such as UXO. These assumptions also imply that magnetic fields are irrotational, and can thus be represented efficiently using a scalar potential.

In the MAS, boundary value problems are solved numerically by representing the electromagnetic fields in each domain of the structure under investigation by a finite linear combination of analytical solutions of the relevant field equations, corresponding to sources situated at some distance away from the boundaries of each domain. The "auxiliary sources" producing these analytical solutions are chosen to be elementary dipoles/charges located on fictitious auxiliary surface(s), usually conforming to but offset slightly from the actual surface(s) of the structure. Enforcement of standard electromagnetic boundary conditions at an array of points over the object's actual surface allows us to solve for the auxiliary sources, from which we can immediately express all EM fields in the problem.

In published work we have described data acquisition and results for a magnetically susceptible half space and a steel sphere along with several experimental and numerical results which show the EMI response from magnetically susceptible soils with rough surfaces. The near and far field effects have been analyzed.

3 Publications

3.1 Papers published in peer-reviewed journals

[1, 12, 24]

3.2 Papers published in non-peer-reviewed journals or in conference proceedings

[13, 14, 17, 18, 25–28]

3.3 Papers presented at meetings, without conference proceedings

[23, 29, 29, 30]

3.4 Manuscripts submitted, but not published

NA

3.5 Technical reports submitted to ARO

NA

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